THE EFFECTS OF TARGET VIBRATION ON THE
HUMAN CONTRAST SENSITIVITY FUNCTION

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(ABSTRACT)

A great deal of research has been conducted on the effects of vibration on visual acuity. The human contrast sensitivity function (CSF) has also been studied extensively as a predictor of visual performance under real-world conditions. However, no previous studies have combined the two lines of research and examined the effect of vibration on the CSF. Prior research indicates that increasing rates of vibration correspond to a decrease in traditional measures of visual acuity. However, other studies indicate that motion enhances target detection. The present study examined the effects of vibration upon the CSF and found that vibration lowers the threshold of detection for low spatial frequencies but raises the threshold for high spatial frequencies. A loss of contrast at high spatial frequencies due to retinal "smear" may be the cause of this increase in high spatial frequency thresholds under vibration. Physiological mechanisms of motion detection, direction selectivity, and visual pathways are also discussed. This study may have important implications for aerospace medicine and occupations which demand viewing a target or instrument panel under conditons of vibration.

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TABLE OF CONTENTS

List of Tables

List of Figures

Introduction

Static vs. dynamic visual acuity

Visual acuity has traditionally been assessed with standard measures such as the Snellen eye chart, tumbling E's, Landolt C's, or the checkerboard pattern of the Bausch and Lomb Ortho-Rater. Both the target and observer are typically stationary when determining acuity under each of these measures. The smallest static figure that a person with normal vision can resolve is one that subtends one minute of arc on the surface of the retina (Sekuler & Blake, 1990).

However, targets and subjects are rarely stationary in the real world. Ordinary locomotor activities such as walking, running and jumping induce angular acceleration of the head requiring an oculomotor compensation to stabilize the image of an observed object on the retina (Benson & Barnes, 1978). The traditional measures of visual acuity are purely static measures that do not address visual acuity under dynamic conditions (Prestrude, 1987).

Dynamic visual acuity has been investigated for over 50 years. As in static visual acuity, the dependent measure has been the minimum visual angle necessary for target recognition or resolution when the image moves across the retina. The general finding has been that image movement, due either to motion of the target or of the observer, degrades acuity (Prestrude, 1987). The result is that the subject requires larger targets for resolution. It is generally accepted that dynamic visual acuity (DVA) is poorer than static visual acuity (Sekuler & Blake, 1990). Thus, DVA should predict performance in dynamic visual

environments such as vehicle operation and sports. Prestrude (1987) further suggested that DVA should be a significant factor in safe and efficient aircraft operation.

An aspect that has not been studied is the effects of motion on target detection (vs. resolution). Movement should actually aid in target detection. For example, a natural defense for many small animals in the wild is to remain motionless in order to avoid detection: movements would betray their position to a predator.

The human contrast sensitivity function

In the real world, the ability of humans and animals to perceive a target is dependent upon the relative size of the target and their visual system's ability to discern contrasts between adjacent areas (Campbell & Maffei, 1974; Campbell & Robson, 1968). The ability to discern contrasts at threshold is a task of target detection, not resolution. Resolution requires higher levels of contrast to identify the target (Campbell & Robson, 1968). The standard optometrist's test to determine visual acuity tests only our resolution of small targets at very high contrast. An alternative measure of visual ability which addresses target detection is the contrast sensitivity function (CSF). Unlike normal measures of visual acuity in which size alone limits vision, the CSF is a measure of how both size and contrast limit vision (Sekuler & Blake, 1990). Sensitivity to contrast is a function of the target's size, normally referred to as spatial frequency. Spatial frequency is the number of complete cycles of a sinusoidal waveform which varies in brightness in a grating pattern over a given distance

(Campbell & Maffei, 1974). Peak sensitivity for human subjects is generally in the range of 3-5 cycles per degree of retinal subtense.

It has been suggested that the CSF may be a better predictor of real-world visual performance than traditional measures of acuity. Ginsberg, Evans, Sekuler, and Harp (1982) found that a pilot's CSF is a good predictor of his ability to see targets on the ground under conditions of reduced visibility. They also found that the pilot's standard clinical measure of visual acuity was not.

As the CSF is a useful predictor of real-world visual performance, it is logical that it should be investigated under dynamic conditions that more closely simulate real-world conditions. The Committee on Vision of the National Academy of Sciences (1984) recommended the determination of Dynamic Contrast Sensitivity Functions (DCSF) to investigate the relationship between dynamic visual acuity and flying.

Motion and vibration

A type of target or observer motion is simple sinusoidal vibration. People, especially pilots and motor vehicle operators, are often required to view targets that vibrate. This vibration can affect targets inside the cockpit, as well as outside. Instrument panels vibrate at a harmonic frequency induced by the engine. It is reasonable to assume that this vibration will make the reading of those instruments more difficult. Also, images of exterior targets must pass through optically imperfect transmission media such as windshields and canopies. If these windshields vibrate, the image that is passed through may also vibrate. Likewise, this applies to ground vehicles, especially trucks,

military vehicles, and heavy equipment.

Coerman (cited by Lange & Coerman, 1962) studied the effects of sinusoidal longitudinal (x-axis) vibration from 20 hz to 140 hz on the visual acuity of seated subjects. He found maximal effects from 25 - 40 hz and 60 - 90 hz. O'Hanlon & Griffin (1971) found a direct relationship between target vibration frequency and error rates from 5 - 40 hz. Schoenberger (1975) reported that the eye can track a vibrating target at very low frequencies. Benson and Barnes (1978) found a general decrease in the numbers of figures seen from 1-10 Hz, with a peak error rate at 3 Hz. They suggested that the eye's pursuit reflex breaks down above 1-2 Hz, but is partially compensated by the vestibulo-ocular response at up to 10 Hz if the subject's head is also subject to the same vibration. Lange & Coerman (1962) studied vibratory effects from 1 - 20 hz "because these frequencies occur frequently in ground, air, and space vehicles." They reported an increase in visual acuity at 1, 2, and 4 c/s. Bond & Moore (1990) stated that the peak vibration energy for a fighter-class aircraft on a low altitude, high speed flight is in the 0.5 - 3.0 hz range.

Vibration and the CSF

We have already seen that the statically-determined human contrast sensitivity function is a better predictor of real-world visual performance than traditional measures of static visual acuity. An obvious question, following this line of inquiry, is what effect does vibration have on the CSF? Although there have been many prior studies investigating the effects of vibration on resolution of traditional

targets, none have addressed the effects of vibration of the CSF. The CSF is a target detection (vs. target resolution) task (Campbell & Robson, 1968). A brief pilot study conducted at Virginia Tech (Arrington, Bowser, & Boyle, 1986) suggested that target vibration may increase contrast in the test target, thereby aiding detection.

Lange & Coerman (1962) stated that there are three possible methods to study vibratory effects on visual acuity. The first is that the subject can be moved while the target remains still. Second, the subject can remain motionless and the target vibrates. Third, both subject and target can vibrate, either in or out of phase. Several prior studies have assessed the effects of subject-only vibration or subject-target vibration on visual acuity (Collins, 1973; Griffin, 1975a, 1975b, 1976; Griffin & Lewis, 1978; Lange & Coerman, 1962: Lewis & Griffin, 1980) but few have addressed the effects of a target vibrating independently of the observer. Arrington et al. (1986) studied this aspect but obtained no conclusive findings.

In a review of the literature, Collins (1973) suggested that the primary source of visual decrement below 10 Hz is probably due to display vibration. It can be argued that body tissues dampen vibration at frequencies in this range. For these reasons, and also to avoid any possible physiological side-effects, this study investigated target-only vibration.

My intention for this study was to examine the effects of target vibration upon contrast sensitivity functions in the range of frequencies from 1 - 10, 15 and 20 Hz. This is the range that pilots and vehicle operators are normally subjected to and that target-only

vibration is the primary source of visual decrement. Previous studies (Benson & Barnes, 1978; O'Hanlon & Griffin, 1971) found a direct relationship between vibratory frequency and error rates. Therefore, I expected that the contrast sensitivity function (CSF) would decrease directly with increasing vibratory frequency. However, evidence gained during a pilot study indicated that target vibration may make target detection easier. This corresponds to Sekuler and Levinson's (1977) finding that, at a very low contrast, a target's motion may be visible even if its pattern is not. Therefore, I was interested to determine if vibration could enhance the detection of some targets.

The data were closely examined to determine if any systematic interactions emerged. Additionally, given the findings of Benson and Barnes (1978) and Lange and Coerman (1962), the range of frequencies from 1 - 5 hz were examined closely to determine if the CSF is enhanced in this range.

Data gained during a pilot study supported the hypothesis that the CSF declines with increased frequency of vibration. However, only five subjects were used and the data base is small. Therefore, the present study employed more subjects in order to gain greater statistical power. This was intended to reveal a main effect for vibration and any interactions between vibratory and spatial frequencies.

Methods

Pilot Study

A pilot study was conducted to test the equipment and procedures to be used in this experiment. Four graduate students and one faculty member served as the subjects. They were exposed to a series of sine wave gratings of varying spatial frequencies and contrast ratios to determine their contrast sensitivity function at various vibratory frequencies. The vibratory frequency was held constant while the sine wave gratings were changed. The contrast was changed across one spatial frequency to determine the threshold at that frequency, then the spatial frequency was changed. Once a CSF was determined for a given vibratory frequency (by determining the threshold for each discrete spatial frequency), the rate of vibration was changed and the procedure repeated.

Both the method of limits and the method of constant stimuli were tested (Gescheider, 1985). The method of constant stimuli was selected for this study as it controls for errors of anticipation and habituation common with the method of limits. Additionally, the method of limits is disruptive to employ, given the equipment and space configurations in the laboratory. The method of limits requires the experimenter to repeatedly stand up in front of the subject to manually advance the carousel slide tray to the next spatial frequency. The method of constant stimuli allows the experimenter to proceed through each slide

tray with no interruption.

Twelve spatial frequencies and 198 slides of sine wave gratings were used in the pilot study. This was narrowed to 10 spatial frequencies and 120 slides (including 12 catch trials) for the present study. As a result of the pilot study, it was also decided to require the subjects to wear noise-reducing earmuffs to reduce or eliminate audio cues to vibratory frequency.

Subjects:

The subjects were 20 undergraduate psychology students, 11 females and 9 males. The ages ranged from 18 to 23; the average age was 21.85. Every subject received class credit for participating in the study. All subjects were screened for near and far binocular visual acuity prior to participating in the experiment. All subjects had corrected far visual acuity of 20/25 or better. All subjects who normally wore corrective lenses wore them during the course of the experiment. The experiment was approved by the VPI & SU Human Subjects Review Board.

Apparatus:

A Bausch and Lomb Modified Ortho-Rater, model 6000, was used to screen each subject for near and far static binocular visual acuity.

The subjects viewed a fine ground glass screen with the test target projected from the rear. The test targets were projected by a Kodak Ektagraphic Carousel slide projector mounted at a right angle to the

screen. A neutral density filter affixed to the lens of the projector reduced glare. A front surface mirror, mounted at a 45 degree angle to both the projector and the rear of the screen, reflected the image onto the screen from the rear. The mirror was mounted horizontally on a bracket affixed to a Bruel & Kjaer Type 4810 Minishaker. The minishaker vibrated the mirror which then caused the image to vibrate laterally (y-axis) on the screen.

An 800-watt Altec model 9440A audio amplifier supplied power to the minishaker. Average output from the amplifier was maintained at 2 volts as measured by a Micronta 20,000 ohms/volt multitester. A signal generator produced a sine wave signal which was amplified by the amplifier and then drove the minishaker. The sine wave frequency was calibrated from 1 to 20 hz with a Southwest Technical Products Corp. Universal Frequency Counter.

The test targets were a series of 108 slides of sine wave gratings produced by VAX computer on a Perceptics Color Image Processor. The slides were photographed by a Matrix Instruments Model 4007 Color Graphic Camera using 100 ASA Kodak Ektagraphic slide film (see acknowledgements, p. iii). The spatial frequencies of the test targets ranged from 0.5 to 26 cycles per degree. Contrast ratios ranged from .756% to 60.7%, as determined by the formula (L-D)/(L+D) (L=light; D=dark). The actual contrast ratios were empirically determined with a Gamma Scientific Radiometer (see acknowledgements, p. iii). The average luminance values of the peaks and lows were determined and used to determine the contrast ratio. Twelve additional targets had extremely high spatial frequencies and were beyond detection. These targets

appeared as a uniform gray and were intended to serve as catch trials. They were randomly spaced throughout the order of presentation. All of the targets were presented vertically in order to avoid any effects of orientation differences such as the oblique effect (Sekuler and Blake, 1990).

Each subject were seated at a table with his/her chin in a chin rest. The chin rest was positioned to keep the plane of the subject's eyes level with the screen and at a constant distance of 43.1 inches so that the target subtended 2 degrees of retinal arc. A flat black muslin tunnel was affixed to a frame which surrounded the subject's head at one end and the frame for the ground glass screen at the other. The subject viewed the test targets through this tunnel. This was intended to eliminate any extraneous visual stimuli. The subject wore noise reducing earmuffs during testing to attenuate any possible auditory cues to the vibratory frequency.

Procedure:

A Bausch and Lomb Modified Ortho-Rater, model 6000, was used to determine a standard measure of binocular far and near static visual acuity for each subject.

The room lights were extinguished for the testing in order to eliminate glare and extraneous visual stimuli. The only source of light other than the test targets was a 25-watt red light bulb shielded by an aluminum cowling for the experimenter to record responses. The subjects were allowed 10 minutes to adapt to the darkened room. Full dark

adaptation was not deemed necessary as the test targets were sufficiently bright to require phototopic vision. The average optical power measured at the screen was 0.05 milliwatts, as measured by a Jodon Model 450B Power meter. This provided enough power for normal photopic vision.

The procedure used the method of constant stimuli. The subjects were instructed to indicate whether or not they could discern a visible pattern of vertical bars. They were asked to answer "yes" or "no" as quickly as possible, within 2-4 seconds, and then the test target was changed. These rapid presentations were intended to avoid grating adaptation which could affect the measured threshold (Albrecht, Farrar, & Hamilton, 1984; Movshon & Lennie, 1979). The subjects were shown high contrast sine wave gratings for every spatial frequency prior to testing to familiarize them with the test targets. A static contrast sensitivity function (no vibration) was determined for each subject to serve as a within-subjects control procedure.

For each condition, the vibration of the mirror was set at one vibratory frequency. The subject viewed test targets of one spatial frequency at a time but at varying levels of contrast in a random order. A contrast threshold was determined for each spatial frequency under that condition. These thresholds established the subject's contrast sensitivity function (CSF) for that vibratory frequency. There was at least one catch trial for every spatial frequency, with a total of 12 catch trials randomly spread across 10 spatial frequencies. If a subject hit on more than half of the 12 catch trials, those data were not used and that condition was tested again at a later date.

Once the CSF was determined under one condition, the vibratory frequency was changed and the CSF determined for the new vibratory frequency. This procedure continued until each subject had been tested under all conditions of vibration. The vibratory frequencies from 1-10 hz, 15 hz, and 20 hz were tested. No subject was allowed to test for more than one hour during any one session in order to avoid fatigue effects.

A comparison stimulus (a high contrast sine wave grating) was placed at each end of a set of slides of one spatial frequency so that the carousel could be presented forward or backward in order to mix up the order of presentation of spatial frequencies. Two trials were conducted for each vibratory frequency, with the average of the two thresholds serving as the subject's threshold. The order of vibratory frequencies was randomized within each session.

Procedures by which sine wave gratings were produced and contrasts measured in previous studies were often left undescribed. The gratings were generally displayed on video display terminals or photographic prints. Campbell and Maffei (1974) acknowledged the loss of contrast in gratings due to reproducing these gratings by a photographic process. This raises questions about the fidelity of those gratings. Most previous studies have been remiss in describing the materials, their production, and the manner in which they determined their contrast ratios. This topic was of great concern to this author so great care was taken to produce and empirically measure the gratings used in this study. I believe that these gratings are as accurate, or better, than those used in any existing study (see page 9 for details of production and scanning. See figure 5 for profiles of typical gratings).

Results

Each subject's average threshold contrasts which determined the contrast sensitivity function at each vibratory frequency were compared in a repeated measures ANOVA. Main effects for vibration and spatial frequency were determined. A significant interaction was also found between spatial frequency and vibratory frequency (see Table 1).

Insert Table 1 about here

A visual inspection of the resulting average contrast sensitivity functions across subjects at 1 to 3 Hz vibration revealed a slight increase in sensitivity to contrast at low (0.5 - 1.75 cycles/degree) spatial frequencies. There is relatively little effect in the mid-range (3.5 - 8 cycles/degree) or higher spatial frequencies (13 - 26 cycles/degree) at this level of vibration (see Figure 1).

Insert Figure 1 about here

The CSF for 1 Hz was not significantly different from that for 0 Hz (see Tables 2 & 3). The overall CSFs for 2 and 3 Hz were significantly different (see Table 2) from the no vibration condition. They varied

primarily at 0.5 and 1.75 cycles/dgree (see Tables 4 & 5). This is a very conservative estimate because the t-test degrees of freedom were reduced from 19 to 3 due to a .1606 Huynh-Feldt correction factor determined in the original analysis of variance.

Insert Tables 2, 3, 4, 5 about here

The average CSFs determined at 4 to 6 Hz vibration show a more marked increase in sensitivity at the low spatial frequencies, little change in the mid-ranges (3.5 and 5 cycles/degree), and a decline in sensitivity for spatial frequencies of 8 cycles/degree and above (see Figure 2). The overall effect is that the CSFs determined under these levels of vibration appear to shift to the left of the CSF determined under static conditions.

Insert Figure 2 about here

The CSF does not actually shift as the thresholds were determined at set spatial frequencies in this research paradigm. The apparent shift is due to the increase in sensitivity at low spatial frequencies and decrease at higher spatial frequencies. The function's peak shifted from 8 to 5 cycles/degree. The CSFs for 4 and 6 Hz vibration were

significantly different from the 0 Hz condition (see Table 2). The 4 Hz curve varied significantly at 0.5 cycles/degree and the 6 Hz curve varied significantly in seven of the 10 spatial frequencies (see Tables 6 & 8).

Insert Tables 6, 7, 8 about here

The overall CSF for 5 Hz was not significantly different but it did vary significantly at four spatial frequencies (see Tables 2 & 7). The reason for this result is unclear.

The CSFs determined at 7, 8, and 9 Hz show the same trend, with a slightly lower sensitivity at the highest three spatial frequencies as compared to 4, 5, and 6 Hz (see figure 3).

Insert Figure 3 about here

The CSFs for 7, 8, and 9 Hz were all significantly different from the 0 Hz condition (see table 2). Once again, the lowest and highest spatial frequencies varied significantly from the control condition (see Tables 9, 10, 11).

Insert Table 5 about here

At 10 Hz and above, sensitivity to the mid-range spatial frequencies is degraded significantly. Moreover, the depression in sensitivity in the higher spatial frequencies is especially pronounced (see figure 4).

Insert Figure 4 about here

Sensitivity to the lowest two spatial frequencies is still somewhat enhanced but the peak of the function is significantly depressed from the static condition. The CSFs for 10, 15, and 20 Hz are significantly different from the 0 Hz condition (see table 2). The highest and lowest spatial frequencies are strongly affected as can be seen by the low p-values (see Tables 12, 13, 14). Even 3.5 cycles/degree, the center of the range (and least affected at lower levels of vibration), is significantly depressed at 15 Hz.

Insert Tables 12, 13, 14 about here

Discussion

The results clearly indicate that moderate levels of target vibration increase sensitivity to low spatial frequencies and decrease sensitivity to high spatial frequency details. The degrading effect on high spatial frequencies corresponds to the general increase in error rates for subjects required to read small target letters under conditions of vibration (Benson & Barnes, 1978). The results also show that higher vibratory frequencies (10 Hz and above) cause the peak of the contrast sensitivity function to be depressed. The immediate implications are, 1) that low spatial frequencies (such as the outlines of pedestrians on the roadside or the outlines of vehicles or aircraft) become more visible in low-contrast conditions if the image of the target is vibrating due to transmission through a vibrating windshield or canopy, and, 2) that resolution of small, fine-detail targets (such as road signs viewed at a distance or fine lettering or other detail on aircraft or vehicle instrument panels) is degraded and requires more contrast than under static conditions.

In retrospect, these conclusions appear intuitively obvious. However, the results empirically confirm these conclusions and enable us to make predictions about human visual performance when people are required to view targets subject to vibration. This is especially critical when considering the design of aircraft and helicopter instrument displays and when trying to predict the visual performance of their pilots under low-light conditions. Benson & Barnes (1978) suggested that pilot vibration induces an ineffective vestibulo-ocular

their pilots under low-light conditions. Benson & Barnes (1978) suggested that pilot vibration induces an ineffective vestibulo-ocular response to vibration in the range from 1-10 Hz. They said this would require a space-stabilized helmet-mounted display to compensate for angular increments of the head, assuming that the head and helmet-mounted display have the same rate of vibration. Even if this action is taken, the vibration of the display may be out of phase with the eyes due to differing material properties such as damping by tissue in the eyes' orbits, thereby degrading fine acuity, as these findings would suggest. The Federal Aviation Administration may also be interested in these findings and their implication for the testing and licensing of pilots.

The contrast sensitivity function has been shown to be a better predictor of real-world visual performance than standard clinical tests of acuity (Ginsburg et al., 1982). At very low contrast, a target's motion may be visible even though the characteristics of its pattern are not (Sekuler & Levinson, 1977). Presumably, in a similar manner, a target that is too small to be resolved accurately may be easily detected if it is in motion. Sekuler and Levinson (1977) suggested that the existence of two separate thresholds for the perception of motion and the perception of pattern are evidence of two separate visual channels in the human nervous system for analyzing these two aspects of a moving target.

This leads to a paradox. If motion aids target detection and the CSF is a target detection task (Campbell & Robson, 1968), why is the curve increasingly depressed at the higher spatial frequencies as

vibration increases? One answer may be retinal "smear", a blurring of the contrast between adjacent areas on the retina so as to degrade image contrast and the eye's ability to detect high frequency targets at low contrast. This effect is analogous to the concept of disability glare: a loss of contrast due to light scatter on the retina (Kaufman, & Christiansen, 1984; Olson, 1988; Pulling, Wolf, Sturgis, Vaillancourt, & Dolliver, 1978). If the target is small enough (i.e. high spatial frequency), then higher levels of vibration could effectively nullify the available contrast due to image slip on the retina. Therefore, higher target contrasts may be necessary to offset the loss in retinal contrast.

This process would appear to be a product of targets that vibrate. The conclusion that motion aids in target detection (Sekuler & Levinson, 1977) was based upon targets that moved at a uniform speed in a given direction. The targets in the present study were subject to sinusoidal vibration and, therefore, changed direction and accelerated and decelerated repeatedly. The back and forth nature of this type of motion could be expected to blur the distinction between the light and dark areas of a small target. The overall image displacement increased with increasing levels of vibration. If this displacement was greater than the width of a single cycle, then retinal contrast between the light and dark areas would be greatly reduced. The center-surround receptor fields would, therefore, not have the necessary contrast to produce the lateral inhibition necessary for the ganglion cell to fire. This can explain the increasing degradation of contrast sensitivity for high spatial frequencies as vibration increased.

Detection of the lower spatial frequencies, by comparison, was enhanced by vibration. As the ratio of target displacement to target size was relatively low, the target displacement may have better differentiated the borders between light and dark areas due to this same retinal slip. This enhanced difference between light and dark areas would predictably increase target detection for lower spatial frequencies.

Studies of direction-specific adaptation have indicated that there are separate neural mechanisms in the human visual pathway which are sensitive to motion in a particular direction (Barlow & Hill, 1963; Sekuler & Ganz, 1963). Interestingly, only the motion perception channel is affected by this directional selectivity; the threshold for pattern perception is unaffected (Sekuler & Levinson, 1977). This finding is taken as evidence of separate visual pathways for motion-perception and pattern perception.

The idea of separate visual pathways for different pieces of information is not new. The concentric center-surround receptor fields of retinal ganglion cells operate in an inhibitory manner in order to signal levels of contrast between adjacent areas on the retina (Hubel & Wiesel, 1979). This lateral inhibition is necessary to extract perceptually relevant information (Sekuler & Blake, 1990). Inhibition serves to accentuate the differences between motion of differing directions. These inhibitory processes are not innate; they must be developed with visual experience (Sekuler & Levinson, 1977).

Information transmitted by the retinal ganglion cells goes to the lateral geniculate nucleus (LGN). The retinotopically arranged receptor

fields of the LGN can accentuate contrasts between neighboring retinal regions due to a stronger inhibitory mechanism. The magnocellular cells of the LGN respond most vigorously to contours moving across their receptive field (Sekuler & Blake, 1990). These cells appear to be involved in the motion-perception mechanism.

The LGN sends its information to the visual cortex. The cells of the visual cortex are topographically arranged in layers (Hubel & Wiesel, 1979), often referred to as hypercolumns (Sekuler & Blake, 1990). Simple cells in the hypercolumns are typically attuned to a specific stimulus orientation and placement. Complex cells, on the other hand are not; they are concerned only with orientation. They tend to respond most vigorously to contours moving across their receptive field (Hubel & Wiesel, 1979). These cells also display direction selectivity and, therefoe, appear to be involved in the motion-perception mechanism (Regan, Beverly, & Cynader, 1979). After these separate pieces of information have been extracted from the stimulus, the information is apparently reintegrated at higher levels of processing which complete the perceptual process (Hubel & Wiesel, 1979).

The present study examined the effects of vibration on the motion-detection pathway. The resultant contrast sensitivity functions should be a more accurate predictor of visual ability under conditions of vibration than prior studies which have used primarily standard types of targets. Hopefully, these results meet the challenge of the National Academy of Sciences' (1984) call for the determination of dynamic contrast sensitivity functions. However, this study is only a first step. More research in this area is needed, especially exploring the

effects of subject-only vibration and the interaction between subject and target vibration, both in and out of phase (Lange & Coerman, 1962) and the resultant contrast sensitivity functions.

Given the phenomena of selective adaptation to direction (Sekuler & Levinson, 1977), it may be desirable to determine if humans adapt to a specific level of vibration. Presumably vibratory motion would engage two sets of motion detectors; those sensitive to motion in the two opposing directions along the axis of motion. If the human visual system can adapt to motion in one direction, can it adapt to motion in two directions? If it does, then vibration would increase thresholds as visual neurons fatigue with increasing exposure to the vibrating stimulus. Such a finding would have important ramifications for pilots and other people who must view vibrating stimuli over an extended time.

As intra-ocular light scatter increases with age (Olson, 1988; Pulling et al., 1978), an additional study could explore the effects of subject age as another independent variable. Lastly, as this study was conducted under relatively low ambient light levels, it may be desirable to repeat these procedures under higher ambient light conditions.

TABLES AND FIGURES

TABLE 1

Analysis of Variance Summary Table for

contrast sensitivity functions at threshold

Source	df	MS	F
Vibratory frequency (A)	12	0.00672493	5.55 *
Spatial Frequency (B)	9	30.38573812	337.35 *
A x B	108	0.00541567	5.96 *
Subjects (S)	19		
A x S	228	0.00121097	
B x S	171	0.09007158	
A x B x S	2052	0.00090819	

* $p<.0001$ by the Huynh-Feldt epsilon correction

TABLE 2

Analysis of Variance Summary Table for the contrast between the stated level of vibration and 0 Hz in a quadratic trend

Hz	df	F	p-value
1	1	1.16	.2959 *
2	1	4.84	.0403
3	1	8.82	.0079
4	1	28.53	.0001
5	1	3.20	.0896 *
6	1	27.93	.0001
7	1	6.30	.0213
8	1	14.25	.0013
9	1	19.25	.0003
10	1	5.83	.0260
15	1	9.92	.0053
20	1	13.41	.0017

* not significantly different from 0 Hz

TABLE 3

Comparison of Static CSF (0 Hz)

to CSF determined at 1 HZ

RR: |t| > t(3),.975 = 3.182 (two tail)

Comparison: 0 - 1 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.04924	.02462	2.00
1.0	.01836	.00975	1.88
1.75	.00457	.00200	2.28
2.5	.00215	.00130	1.65
3.5	-.00085	.00117	-.73
5.0	.00062	.00140	.44
8.0	.00059	.00106	.56
13	-.00431	.00314	-1.37
18	-.00113	.00568	-.20
26	-.02237	.01140	-1.96

TABLE 4

Comparison of Static CSF (0 Hz)

to CSF determined at 2 HZ

RR: |t| > t(3),.975 = 3.182 (two tail)

Comparison: 0 - 2 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.07902	.02251	3.51 *
1.0	.02373	.00908	2.61
1.75	.00264	.00200	1.32
2.5	.00360	.00415	.87
3.5	-.00162	.00143	-1.13
5.0	.00143	.00135	1.06
8.0	.00178	.00105	1.69
13	.00075	.00240	.31
18	.00253	.00635	.40
26	-.01387	.02300	-1.21

* $p < .05$

TABLE 5

Comparison of Static CSF (0 Hz)

to CSF determined at 3 HZ

RR: |t| > t(3),.975 = 3.182 (two tail)

Comparison: 0 - 3 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.07471	.02205	3.39 *
1.0	.01817	.00890	2.04
1.75	.00601	.00180	3.31 *
2.5	.00267	.00140	1.91
3.5	-.00139	.00130	-1.04
5.0	.00188	.00121	1.55
8.0	.00065	.0011	.59
13	-.00082	.00258	-.32
18	-.02090	.00903	-2.32
26	-.02200	.01119	-1.97

* $p < .05$

TABLE 6

Comparison of Static CSF (0 Hz)

to CSF determined at 4 HZ

RR: |t| > t(3),.975 = 3.182 (two tail)

Comparison: 0 - 4 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.12562	.04310	5.83 *
1.0	.02544	.00973	2.61
1.75	.00407	.00194	2.10
2.5	.00320	.00150	2.13
3.5	-.00220	.00123	-1.79
5.0	.00159	.00100	1.47
8.0	-.00142	.00110	1.29
13	-.00606	.00263	-2.31
18	-.01781	.00656	-2.72
26	-.03050	.01010	-3.02

* $p < .05$

TABLE 7

Comparison of Static CSF (0 Hz)

to CSF determined at 5 HZ

RR: $|t| > t(3),.975 = 3.182$ (two tail)

Comparison: 0 - 5 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.05500	.02236	2.46
1.0	.02913	.00814	3.58 *
1.75	.00709	.00171	4.16 *
2.5	.00676	.00154	4.40 *
3.5	.00055	.00106	.52
5.0	.00216	.00093	2.34
8.0	-.00323	.00183	-1.77
13	-.00465	.00239	-1.95
18	-.01763	.00740	-2.39
26	-.03848	.01999	-3.85 *

* $p < .05$

TABLE 8

Comparison of Static CSF (0 Hz)

to CSF determined at 6 HZ

RR: |t| > t(3),.975 = 3.182 (two tail)

Comparison: 0 - 6 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.12244	.02073	5.91 **
1.0	.03558	.00886	4.02 *
1.75	.00523	.00197	2.66
2.5	.00477	.00146	3.28 *
3.5	-.00078	.00124	-.63
5.0	.00039	.00116	.34
8.0	-.00598	.00148	-4.05 *
13	-.03384	.00618	-5.48 *
18	-.04654	.00945	-4.92 *
26	-.04610	.01022	-4.51 *

* p < .05

** p < .01

TABLE 9

Comparison of Static CSF (0 Hz)

to CSF determined at 7 HZ

RR: $|t| > t(3),.975 = 3.182$ (two tail)

Comparison: 0 - 7 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.08707	.02600	3.35 *
1.0	.03096	.00885	3.50 *
1.75	.00431	.00191	2.26
2.5	.00378	.00150	2.52
3.5	-.00086	.00133	-.65
5.0	.00044	.00123	.36
8.0	-.00370	.00798	-.46
13	-.01283	.00365	-3.52 *
18	-.02882	.00963	-2.99
26	-.04714	.00880	-5.36 *

* $p < .05$

TABLE 10

Comparison of Static CSF (0 Hz)

to CSF determined at 8 HZ

RR: |t| > t(3),.975 = 3.182 (two tail)

Comparison: 0 - 8 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.12152	.02310	5.26 *
1.0	.03072	.00905	3.40 *
1.75	.00320	.00174	1.84
2.5	.00479	.00140	3.42 *
3.5	-.00292	.00119	-2.45
5.0	.00038	.00122	.31
8.0	-.00370	.00798	-.46
13	-.03018	.00763	-3.95 *
18	-.04481	.01035	-4.33 *
26	-.04896	.00963	-5.08 *

* $p < .05$

TABLE 11

Comparison of Static CSF (0 Hz)

to CSF determined at 9 HZ

RR: $|t| > t(3),.975 = 3.182$ (two tail)

Comparison: 0 - 9 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.12773	.01988	6.43 **
1.0	.02421	.00973	2.49
1.75	.00380	.00215	1.77
2.5	.00087	.00130	.67
3.5	-.00099	.00124	-.80
5.0	.00005	.00140	.04
8.0	-.00325	.00113	-2.89
13	-.02090	.00432	-4.84 *
18	-.03077	.03076	-1.00
26	-.04599	.01072	-4.29 *

* $p < .05$

** $p < .01$

TABLE 12

Comparison of Static CSF (0 Hz)

to CSF determined at 10 HZ

RR: $|t| > t(3),.975 = 3.182$ (two tail)

Comparison: 0 - 10 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.05917	.02588	2.29
1.0	.02379	.00883	2.69
1.75	.00394	.00153	2.58
2.5	.00073	.00120	.61
3.5	-.00199	.00114	-1.75
5.0	-.00010	.00112	.09
8.0	-.00607	.00113	-5.40 *
13	-.03539	.00541	-6.55 **
18	-.05163	.00972	-5.31 *
26	-.05329	.00928	-5.75 *

* $p < .05$

** $p < .01$

TABLE 13

Comparison of Static CSF (0 Hz)

to CSF determined at 15 HZ

RR: $|t| > t(3),.975 = 3.182$ (two tail)

Comparison: 0 - 15 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.08412	.02522	3.34 *
1.0	.02285	.00935	2.45
1.75	.00153	.00213	.72
2.5	.00102	.00150	.68
3.5	-.00486	.00134	-3.64 *
5.0	-.00386	.00148	-2.62
8.0	-.00753	.00135	-5.58 *
13	-.03569	.00551	-6.48 **
18	-.06199	.01387	-4.47 *
26	-.05577	.00947	-5.89 **

* $p < .05$

** $p < .01$

TABLE 14

Comparison of Static CSF (0 Hz)

to CSF determined at 20 HZ

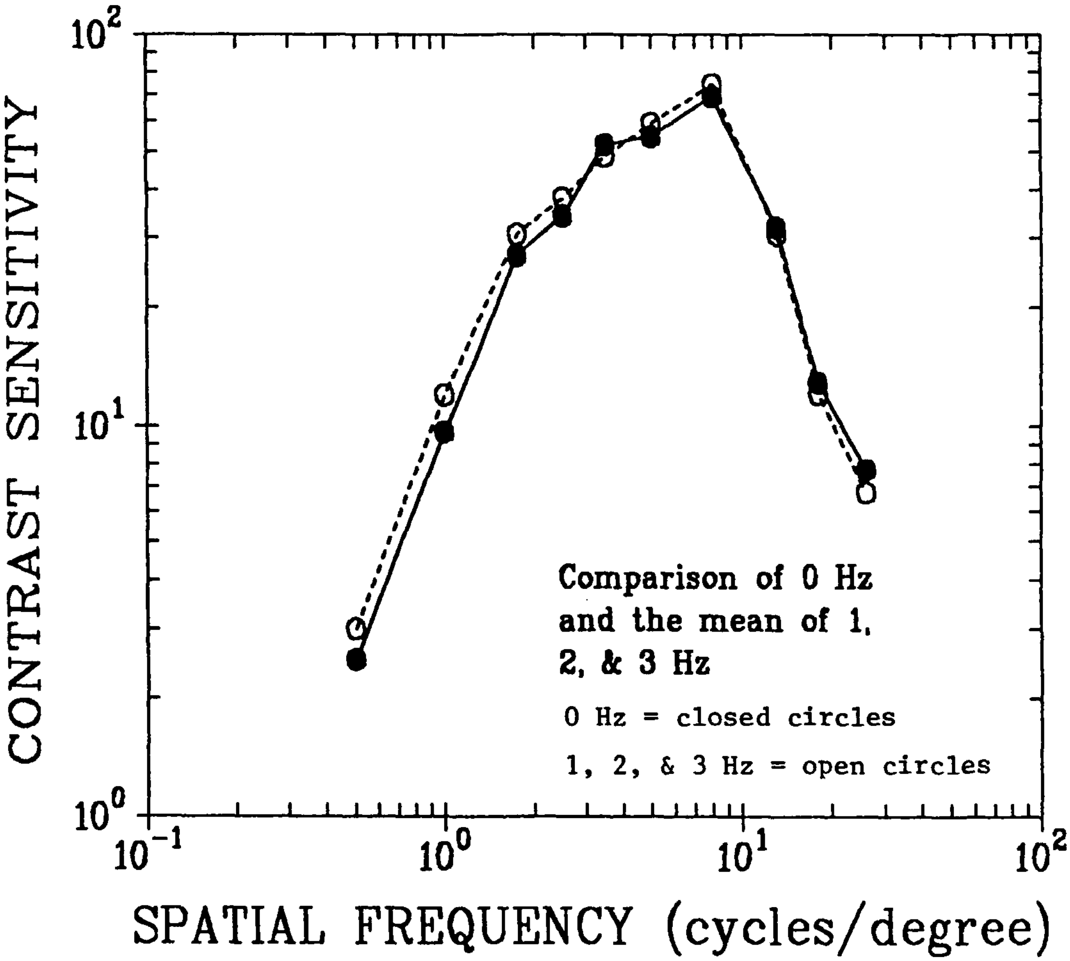
RR: |t| > t(3),.975 = 3.182 (two tail)

Comparison: 0 - 20 Hz

Spatial frequency	Mean Difference	Mean std error	t
0.5	.11169	.02382	4.69 *
1.0	.01917	.00965	1.99
1.75	.00148	.00211	.70
2.5	-.00065	.00145	-.45
3.5	-.00436	.00150	-2.91
5.0	-.00445	.00161	-2.76
8.0	-.01273	.00688	-1.85
13	-.04639	.00750	-6.19 **
18	-.07517	.01020	-7.37 **
26	-.06721	.00896	-7.50 **

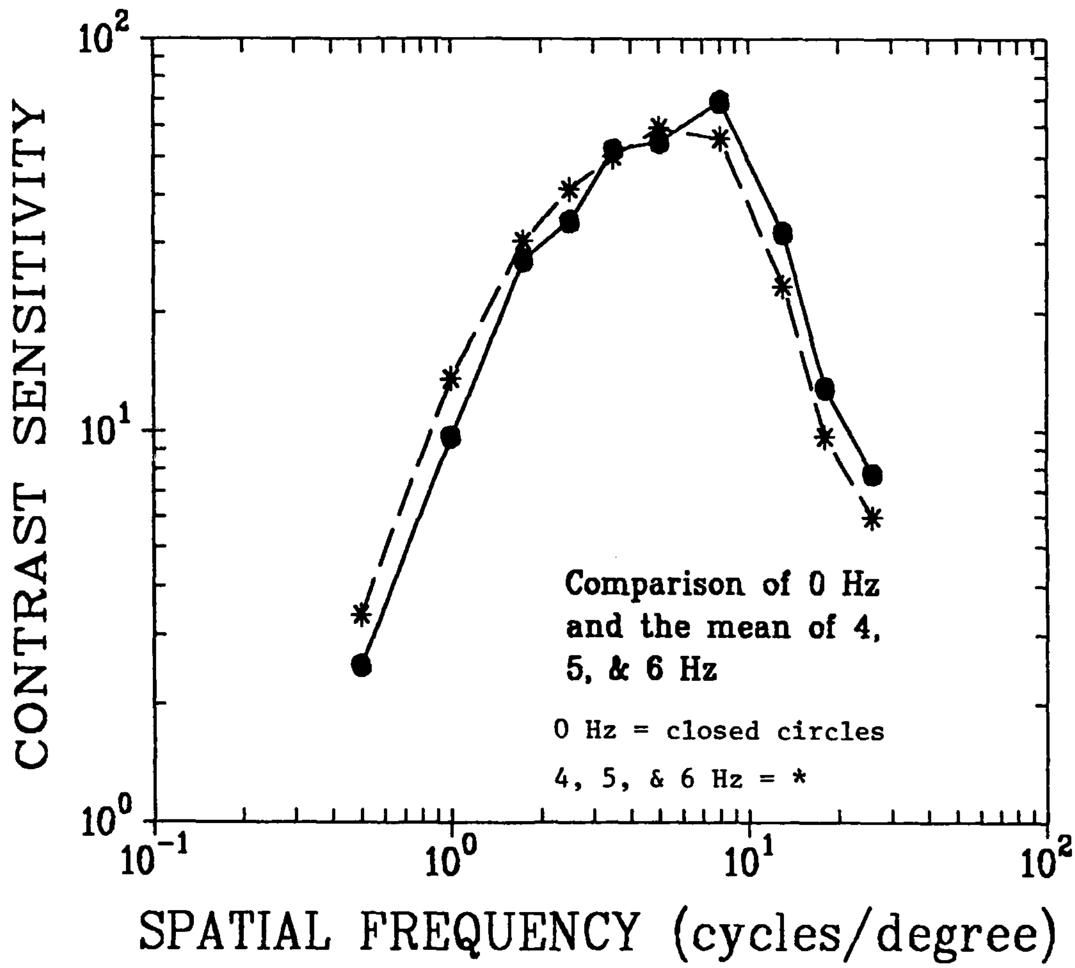
* $p < .05$

** $p < .01$



CONTRAST SENSITIVITY
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
SPATIAL FREQUENCY (cycles/degree)
Comparison of 0 Hz and the mean of 1, 2, & 3 Hz
0 Hz = closed circles
1, 2, & 3 Hz = open circles

FIGURE 1



CONTRAST SENSITIVITY
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
SPATIAL FREQUENCY (cycles/degree)
Comparison of 0 Hz and the mean of 4, 5, & 6 Hz
0 Hz = closed circles
4, 5, & 6 Hz = *

FIGURE 2

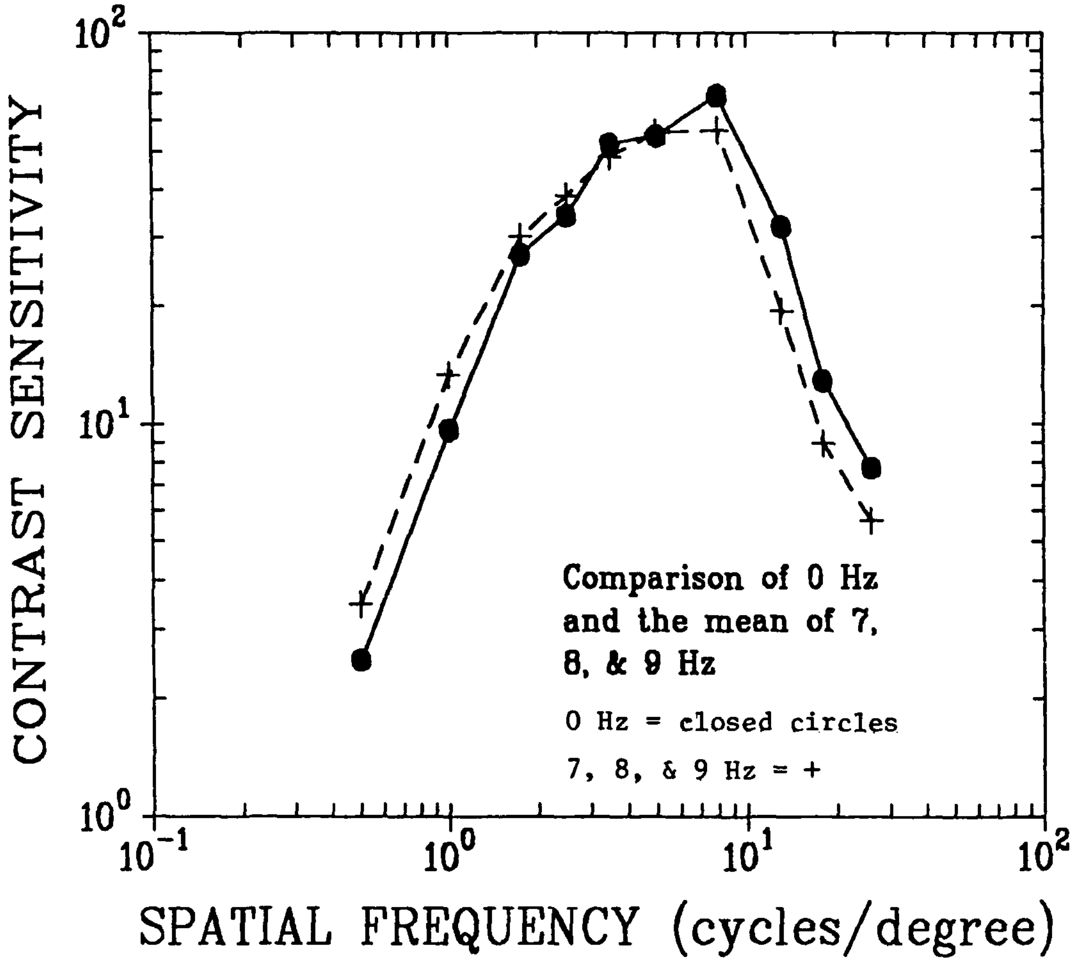
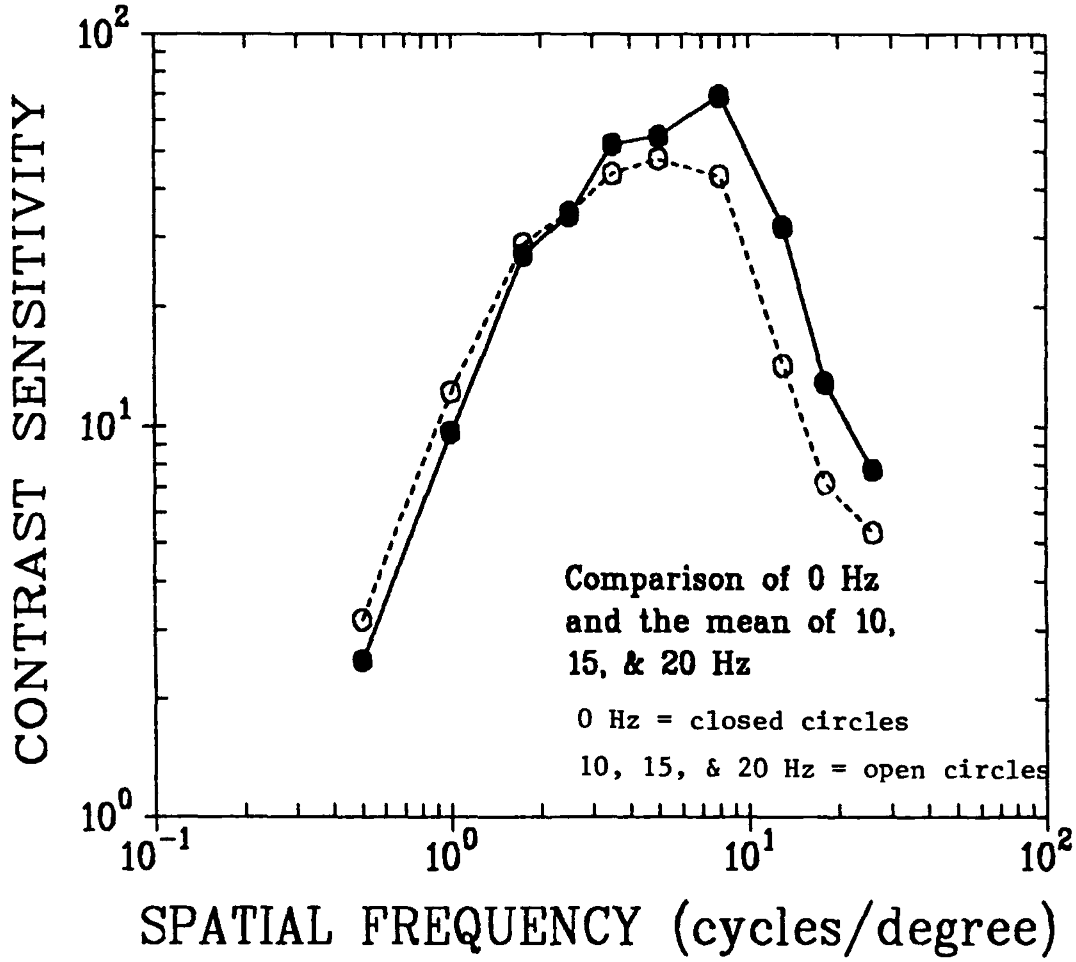

CONTRAST SENSITIVITY
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
SPATIAL FREQUENCY (cycles/degree)
Comparison of 0 Hz and the mean of 7, 8, & 9 Hz
0 Hz = closed circles
7, 8, & 9 Hz = +

FIGURE 3



CONTRAST SENSITIVITY
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
SPATIAL FREQUENCY (cycles/degree)
Comparison of 0 Hz and the mean of 10, 15, & 20 Hz
0 Hz = closed circles
10, 15, & 20 Hz = open circles

FIGURE 4

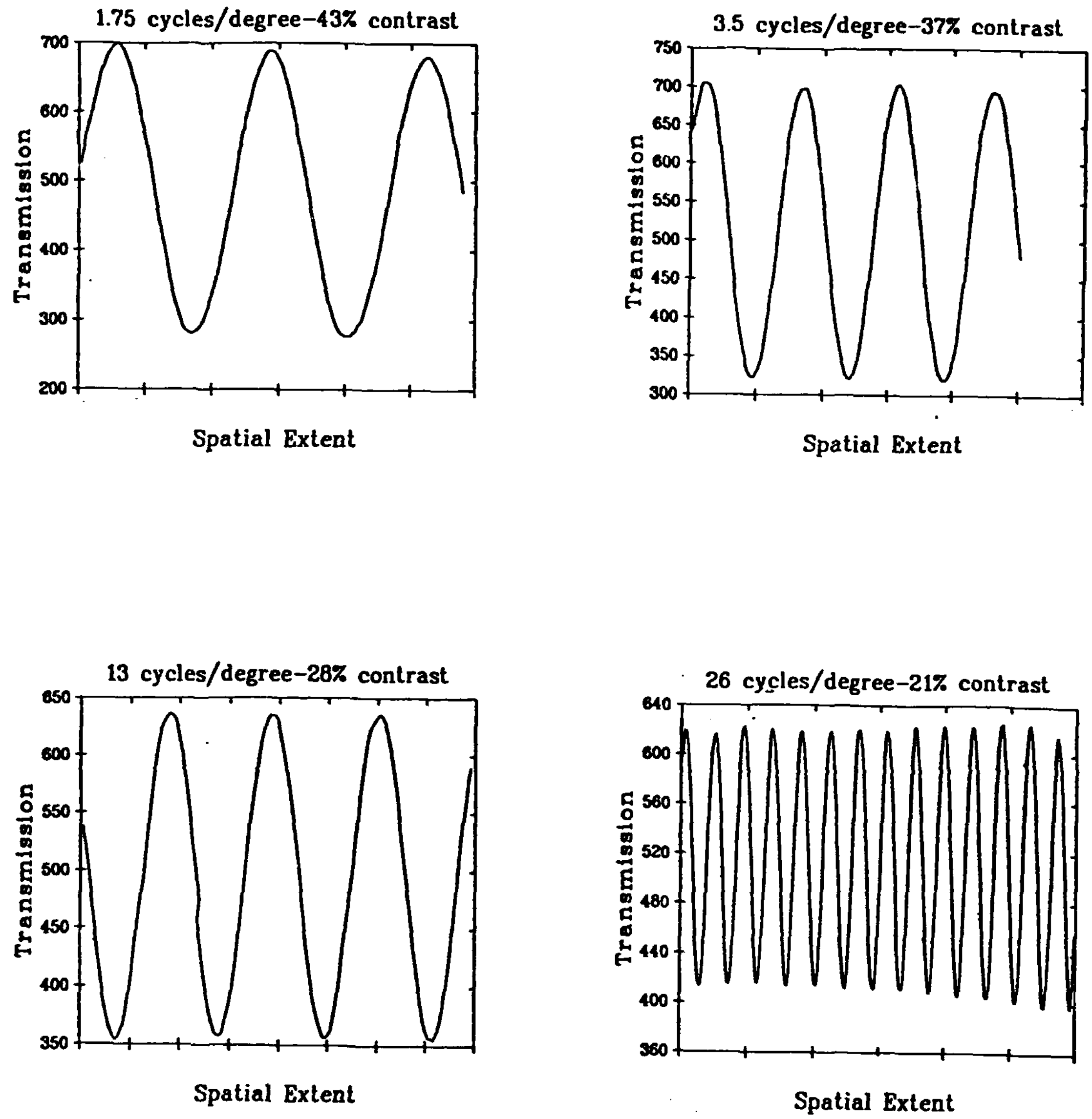


FIGURE 5:

Profiles of typical sine-wave gratings

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Appendix A

Informed Consent to Particpate in Research

DYNAMIC VISUAL ACUITY: EFFECTS OF VIBRATION

(Project Code Number: 1001-91 #001)

Principle Investigator:	William F. Adams 5092A Derring ph: 552-2644	Project Supervisor:	Dr. Albert M. Prestrude 5107 Derring ph: 231-5673

We are studying the effect of target vibration on your ability to detect that target or some feature of that target. Our results are potentially significant for flying, driving, and sports vision. We will be using lights that are no brighter than those you ordinarily experience in everyday conditions. You must be at least 18 years old to participate or else receive your parents' permission.

At the termination of the study, we will be happy to tell you its purpose and what the results were. We will tell you specifically about your own performance. We will also screen your vision prior to testing and tell you the results immediately. Although this procedure is not a substitute for a thorough eye exam by an optometrist or opthalmologist, we can tell you if your visual acuity is normal for your age group.

You may terminate your participation at any time, without penalty or jeopardy to your course grade from terminating your participation. Of course, experimental points will be awarded only for those sessions in which you participate. After your initial visual screening and first hour-long session, you may be called back to participate in up to four more sessions. You will receive one experimental credit for each hour-long session you participate.

If you have any questions, please contact the Principle Investigator or Project Supervisor above or Dr. Helen Crawford, Head of the Human Subjects Committee, Department of Psychology, 5070C Derring, 231-6520.

I have read the above description and agree to participate in the study, Dynamic Visual Acuity: Effects of Vibration. I understand that the results will be available to me, but will be kept confidential. I may discontinue my participation at any time without penalty.

Signature:____________________________________

Student No.:__________________________________

Date:____________________

Appendix B

INSTRUCTIONS TO THE SUBJECT

Please have a seat at the table and place your chin in the chin rest provided. You may adjust it up or down according to your height by the silver adjusting knob at the base. You are asked to keep your chin in the chin rest at all times during this test.

In this task you are asked to look at the circle of light on the screeen in front of you and determine whether or not you can discern a pattern of vertical bars. The images may be very faint or non-existent so you are asked to guess, even if you only think you see a pattern. You will not see a pattern on every target so do not become discouraged if you do not see one.

Answer "yes" or "no" based upon your initial reaction. Please answer as quickly as possible and do not spend too much time on any one image.

I will now give you a demonstration of the types of images you may see. (NOTE: Present demonstration high-contrast targets).

Do you have any questions before we begin?

If not, then please don the noise-reducing earmuffs that are on the table in front of you and keep them on until told to remove them.

Appendix C

DATA COLLECTION SHEET

SUBJECT:____________________AGE:______FAR, NEAR ACUITY:____________CORRECTED?______

DATE:______________VIBRATORY FREQUENCY, TRIAL #:_______________EYE COLOR:___________

PERIOD	SPATIAL FREQUENCY	CONTRAST LEVELS (Circle = yes, X = no)															
(Tray #1)																	
250	(0.5 cy/deg)	75	50	35	15	UG	20	10	30	40	25	75					
125	(1.0 cy/deg)	50	8	7	2	UG	25	3	6	20	15	10	1	5	9	4	50
65	(1.75 cy/deg)	50	9	6	UG	.8	4	7	8	3	.9	2	UG	1	5	50	
50	(2.5 cy/deg)	50	.8	10	.9	8	6	4	7	3	UG	1	9	5	2	50	
33.5	(3.5 cy/deg)	50	7	4	5	1	10	.8	8	6	2	.9	3	UG	50		
(Tray #2)																	
25	(5 cy/deg)	50	3	2.5	5	.5	1	7	UG	6	2	4	1.5	50			
17	(8 cy/deg)	50	6	.8	10	1.5	3	.9	2	5	7	4	1	UG	8	9	50
10	(13 cy/deg)	50	6	5	UG	15	UG	7	9	1	8	10	3	2	20	4	50
7	(18 cy/deg)	75	40	UG	15	50	20	30	35	60	10	25	45	75			
5	(26 cy/deg)	100	75	UG	30	35	70	25	60	15	40	20	65	50	10	100	

Observed Thresholds:

0.5 cy/deg:______ 2.5 cy/deg:______ 5 cy/deg:______ 18 cy/deg:______

1.0 cy/deg:______ 3.5 cy/deg:______ 8 cy/deg:______ 26 cy/deg:______

1.75 cy/deg:______ 13 cy/deg:______

Tested by:____________________

Appendix D

Empirically Determined Contrast Ratios

Spatial Frequency	Slide	Contrast
0.5 Cy/deg	250-10	.11369
	250-15	.16703
	250-20	.21011
	250-25	.25240
	250-30	.31024
	250-35	.34181
	250-40	.38936
	250-50	.47275
	250-75	.60761
1.0 cy/deg	125-3	.02758
	125-4	.04658
	125-5	.05710
	125-6	.06162
	125-7	.07254
	125-8	.08223
	125-9	.09176
	125-10	.08902
	125-15	.12589
	125-20	.16862
	125-50	.43406

1.75 cy/deg	65-.8	.01856
	65-.9	.01553
	65-1	.0170
	65-2	.02510
	65-3	.03262
	65-4	.03968
	65-5	.04947
	65-6	.05857
	65-7	.06845
	65-50	.42603
2.5 cy/deg	50-.8	.01250
	50-.9	.01345
	50-1	.01439
	50-2	.02197
	50-3	.03085
	50-4	.03720
	50-5	.04398
	50-6	.05403
	50-7	.05872
	50-8	.06488
	50-50	.38289
3.5 cy/deg	33.5-.8	.01272
	33.5-.9	.01470

	33.5-1	.01344
	33.5-2	.01842
	33.5-3	.02826
	33.5-4	.03627
	33.5-5	.04320
	33.5-6	.04980
	33.5-50	.37218
5.0 cy/deg	25-.5	.00856
	25-1	.01339
	25-1.5	.01336
	25-2	.01736
	25-2.5	.02049
	25-3	.02735
	25-4	.03456
	25-5	.04133
	25-50	.35955
8.0 cy/deg	17-.8	.00756
	17-.9	.01044
	17-1	.01252
	17-1.5	.01066
	17-2	.01684
	17-3	.02574
	17-4	.03017
	17-5	.03774

	17-6	.04664
	17-50	.34445
13 cy/deg	10-3	.02146
	10-4	.02660
	10-5	.03370
	10-6	.04003
	10-7	.04290
	10-8	.05378
	10-9	.06232
	10-10	.05943
	10-15	.08942
	10-20	.12164
	10-50	.28238
18 cy/deg	7-10	.04942
	7-15	.07222
	7-20	.09465
	7-25	.11773
	7-30	.11359
	7-35	.16036
	7-40	.18835
	7-75	.27436
26 cy/deg	5-15	.03995
	5-20	.05850

5-30	.07468
5-40	.09128
5-50	.10539
5-60	.11427
5-65	.14071
5-70	.16170
5-75	.16610
5-100	.20661

Vita

William F. Adams

Born: [redacted]

Social Security Number: [redacted]

Marital Status: [redacted]

Business Address: Department of Psychology
Virginia Polytechnic Institute
and State University

Home Address: [redacted]

Home Phone: [redacted]

EDUCATION

B. S. United States Military Academy
Major Field of Study: Engineering Mechanics

M. S. Virginia Polytechnic Institute & State University
Major Field of Study: Applied-Experimental Psychology

EMPLOYMENT AND PROFESSIONAL SCHOOLING

1977-1981: Cadet, United States Military Academy, West Point, NY

1979: Airborne School, Fort Benning, GA.

1981: Commissioned in the U.S. Army

1981-1982: Attended Motor Officer School, Fort Knox, KY. Field Artillery Officers' Basic Course, Cannon Battery Officers' Course, Fort Sill, OK. Ranger Course, Fort Benning, GA.

1982-1983: Company Training Officer, Aide-de-Camp, Battalion Operations Officer, Fort Dix, NJ.

1983: Jumpmaster Course, Fort Benning, GA.

1984-1986: Battery Fire Direction Officer, Recon Survey Officer, Emergency Actions Operations Officer, Vicenza, Italy.

1987: Field Artillery Officers' Advanced Course, Fort Sill, OK.

1987-1990: Battalion Fire Support Officer, Battery Commander, Plans and Operations Officer, Fort Ord, CA.

1990: Combined Arms and Services Staff School, Fort Leavenworth, KS.

1990-1992: Graduate Student, Virginia Polytechnic Institute and State University, Blacksburg, VA.

HONORS AND AWARDS

Gillmore Trophy for the best firing battery in the Division Artillery, 7th Infantry Division (Light), Fort Ord, CA, Nov. 1989.

Two Meritorious Service Medals

Two Army Commendation Medals

National Defense Service Medal

Army Service Ribbon

Overseas Service Ribbon

Parachutist's Badge

Ranger Tab

Italian Armed Forces Parachutists' Badge

PROFESSIONAL ORGANIZATIONS AND ACTIVITIES:

Member, Association of Graduates, U.S. Military Academy

Member, Order of Saint Barbara

Member, Field Artillery Association

Member, Automatic 8th Association

PUBLICATIONS

Adams, W.F. (1989, Oct.). Tactical Standard Operating Procedures for B Battery, 2nd Battalion, 8th Field Artillery. (Available from Cdr, B Btry, 2/8 FA, Fort Ord, CA 93941).

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